RESEARCH DEPARTMENT

AN INVESTIGATION OF REVERBERATION TIME VARIATIONS AND DIFFUSION OF SOUND IN SMALL ROOMS

Report No. B-070

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SUMMARY

This report describes an investigation of some problems of sound diffusion in rooms, and in some respects carries on the investigation of earlier reports.[1,2]

The experimental work shows that it is possible to measure the degree of diffusion in a room by fairly simple practical techniques; quantities based on the frequency variation of reverberation time and double reverberation decay constants are the most promising for use in small studios.

It is also shown that uniform distribution of absorption can be as effective as other means of attaining conditions of good diffusion. Rectangular diffusers are particularly effective in improving conditions where the distribution of absorption is poor.

1. INTRODUCTION

1.1. Significance of the Term "Diffusion"

A sound field is defined as being completely diffuse if it has uniform energy density within the region considered and if the directions of propagation at any arbitrarily selected points are wholly random in distribution. Although perfect diffusion is thus theoretically identifiable there is no generally accepted method of describing quantitatively a state of diffusion which falls short of perfection.

The importance of a knowledge of the state of diffusion lies in the fact that reverberation formulae (e.g. those of Sabine and Eyring) assume perfect diffusion in a room.[3] Experiments have shown that in normal rooms of reasonable size and for wavelengths appreciably smaller than the dimensions of the room, the formulae are in general valid. The most important use of these formulae in the B.B.C. and elsewhere is to enable the behaviour of an absorbing material in a studio to be predicted from its behaviour in a reverberation room. Since there have been cases where such predictions have proved to be inaccurate, an examination of the mechanism of diffusion is important for this reason alone.

Further, experience shows that a number of undesirable subjective effects in studios are associated with an inadequate degree of diffusion. The work described was all carried out under laboratory conditions, but attention has been directed

throughout to finding practical means for investigating studios where time is limited and apparatus must be easily portable.

The term "diffuse" refers to the sound field itself but the term "diffused" will be used in this report to describe a room where, in the frequency band under consideration, the sound field attains a high degree of diffusion. The term "diffuser" will be used to describe a rigid object possessing a negligible sound absorption coefficient, fixed to a flat surface of a room so as to change the shape of the surface.

A room can be considered as a system having a large number of modes of resonance within the audible range of frequency. The excitation of each of these modes is determined by the position of the source of sound in the room and its frequency, whilst its damping is determined by the absorbing power of the surfaces associated with it. Any surface attains its maximum absorbing power only when sound waves are incident normally upon it; for tangential waves, the coefficient of absorption is in general half the coefficient for normal incidence.

A pure tone present in a room excites a number of modes. The excitation of a particular mode decreases as the frequency interval between the tone and the resonance frequency of the mode increases; in practice therefore the number of modes contributing significantly is limited. The intensity level of sound in a room is at all times the vector sum of the modal responses, and of the exciting tone.

It is customary in the study of the transient (reverberant) response of a room to observe the effect of switching off a steady tone. It should be noted that before switching off a steady tone, the frequency of oscillation (i.e. the forced oscillation) is that of the exciting tone, but at the instant of cut-off each of the modes of the room has associated with it an immediate response in the form of a decay of tone at its own modal frequency.

The resultant decay follows an approximately exponential law where there are a large number of equally excited and equally damped modes substantially sharing the sound energy; there are, however, beats between the modes which are energised at different frequencies, resulting in a modulation of the envelope of the sound decay.

It is convenient at this stage to consider the logarithm of the sound pressure level, i.e. to use a decibel scale. When this is done, a sound decay which is exponential with respect to time becomes a straight-line decay, and oscillations in the exponential envelope appear as oscillations about a mean straight line. In the same way changes of exponential decay constant during the decay appear as changes in slope of the straight line; when the changes are gradual the line exhibits a curvature.

Thus while modulations of the straight-line decay occur as a result of beats between different modes, double-slope or curvature effects may be evident where the component modes do not all have the same damping coefficient. As the number of contributory modes increases, the beats become less evident and curvature effects disappear, because the shape of the decay tends to be controlled by the more lightly damped modes. The decay thus tends to become linear.

It should be noted that a pure straight-line decay may also correspond to the excitation of a single mode. This extreme case cannot occur in a room although conditions approaching it do occur when the modes are so widely separated in frequency

that contributions from adjacent modes are negligible. It is important to distinguish between this type of straight-line decay and that described above.

In the treatment above, we have described the sound field in a room in terms of a system of modes. Using this concept we are led to the conclusion that perfect diffusion is only obtained when the sound energy in the room is carried equally by an infinite number of modes. Although unattainable in practice, this idea is useful as a norm in assessing the degree of diffusion.

1.2. The Mechanism of Diffusion and the Steady-State Characteristic

Resonance in a room arises as a result of successive reflections of sound waves from the room surfaces. The frequencies of the modes of resonance are determined by the time delays between reflections and hence by the geometry of the room. Where the absorbing materials are purely resistive and of negligible depth, the modal frequencies can be only slightly affected by the distribution of absorption over the surfaces of the room. The sound energy associated with each mode, however, will be governed by the absorption coefficients of the surfaces involved in its development. In general, it can be expected that the most uniform distribution of energy between the modes (implying the most uniform distribution through the room) will occur when the absorption coefficient is the same over all the surfaces, because otherwise energy will be concentrated into particular modes. The term "intrinsic" will be used, for the purposes of this report, to describe the degree of diffusion attained under these conditions.

A lower degree of diffusion for a given frequency region will naturally be obtained if the distribution of absorption is poor; an appreciably higher degree of diffusion can only be achieved by changing the shape of the room in some way. A change in the ratio of dimensions may improve the diffusion in a particular frequency region, although possibly at the expense of another part of the audio spectrum. Irregularities introduced into the walls — such as rectangular or other projections — improve the degree of diffusion by separating the modes into a larger number of components.

The above considerations may be summarised in the statement that in a given room where the walls are plane and absorption is not perfectly distributed, the degree of diffusion can be improved up to a maximum intrinsic value by improving the uniformity of the average absorption between the surfaces. Irregularities in the walls, such as are provided by artificial diffusers, are the only means by which the degree of diffusion might be increased beyond this value.

This simple exposition ignores effects due to diffraction occurring, for example, at the edges of patches of absorber and the edges of diffusers. Such effects imply a change of shape of the wave front and will increase the degree of diffusion to a small extent because the direction of propagation of part of the energy is altered.

The importance of this factor cannot be accurately assessed until further work has been carried out. In the work described below the possibility of diffraction effects was borne in mind and the experiments were so devised that as far as possible any such effects would not invalidate the conclusions.

A study of the steady-state frequency response of a room is perhaps the most obvious line of attack for finding a measure of the state of the sound field, as the peaks in the response can be related directly to the resonance frequencies of the modes. This method has been used in earlier investigations.[1,4]

When the source of sound is in one corner of the room and the receiver in another, the peaks of the steady-state response correspond to the mode frequencies, provided that the modes are clearly separated, i.e., if the room is small or the frequency low. As the frequency is increased and the modal separation therefore reduced, the picture becomes complicated by the contributions of adjacent modes. If a state of perfect diffusion existed the modes would not be identifiable in any way.

Corresponding to the steady-state frequency response for any one point in a room, there exists a steady-state spatial distribution in the room for any one frequency. This might also be used as a diffusion indicator.

1.3. Measurements from Fluctuations in Decay Curves

As has been indicated above, beats in the envelope of a sound decay when tone has been cut off will tend to disappear as the degree of diffusion increases; an examination of the amplitude of these beats might therefore be expected to lead to some kind of diffusion index. Analysis of this type has indeed been used in the assessment of concert halls, and a laboratory development of the method was the starting point for the present investigation. Although results from studios and concert halls and some simple laboratory experiments had shown promise, it was clear that a very large number of decays needed to be analysed before any reliable, repeatable results could be obtained. For this reason, an attempt was made to develop an automatic method for measuring a quantity ("D"),[5] defined as the modulus of the mean deviation in decibels of the fluctuating decay curve from the best fit straight line.

The method showing most promise involved measuring not the factor D itself but a related quantity. For this purpose a modification of the equipment built for the measurement of steady-state level irregularity was used.

This equipment was based on a high-speed level recorder and measured the average amplitude of oscillations in the straight-line decay. Readings of this quantity, called for convenience the decay irregularity, were unfortunately very critically dependent on the adjustments of the apparatus. Several room conditions were investigated and it was found that although differences could be detected by very careful control of the conditions of the experiment, especially reverberation time, in general these differences were of the same order as the overall errors of measurement.

The average values of the decay irregularity for three conditions are given in Table 1. These conditions were chosen to represent the maximum possible range of diffusion.

TABLE 1

Results of Measurements of Decay Irregularity

Condition	Reverberation Time	Decay Irregularity
Room with rectangular diffusers	1·0 secs.	15·4 dB
Room empty	1·8 secs.	16.9 ~~18·9~~ dB
Room with absorption concentrated on one wall	0·9 secs.	19·0 dB

The differences between these conditions are not very large, although they are certainly significant. It will be seen that the highest decay irregularity is obtained with a condition where a low degree of diffusion must be expected and the lowest value where steps have been taken to increase diffusion. In particular it will be seen that the last mentioned value is lower than the value for the empty room, which, having uniformly distributed absorption, provides an example of a room with an intrinsic degree of diffusion.

In practice the technique just described appeared to be far too insensitive for practical purposes and work on it was therefore discontinued. A new approach was made to the problem of finding a practical diffusion index. It was decided to set up conditions representing practical extremes of absorption distribution and diffusion, and then to determine what corresponding changes had taken place in the sound field by examining all the quantities which seemed likely to be affected by the degree of diffusion, other than steady-state and decay-irregularity already discussed.

Following from the general concept of diffusion, several properties of a perfectly diffuse sound field can be assumed. These are:

1. The frequency irregularity and spatial irregularity obtained from steady-state measurements will be negligible.
2. There will be negligible modulation of the decay characteristics in the form of beats over a wide range of frequencies.
3. Decays will be perfectly exponential, i.e., they will be represented by single straight-lines on a logarithmic scale.
4. The form of the decay will be independent of the measuring position in the room.
5. The character of the decay will not be critically dependent on frequency.
6. The character of the decay will be independent of the directional component of velocity used for measurement.

The characteristics under items 1 and 2 above having already been studied, attention was concentrated on the remainder of these properties of a perfectly diffuse sound field. The first series of experiments was restricted to a study of the average slope of the decay, measured as reverberation time.

2. FIRST SERIES OF MEASUREMENTS USING REVERBERATION TIME STATISTICS

2.1. Methods of Measurement and Analysis

All tests were carried out in a tiled room approximating to a 10 ft (3·04 m) cube. The prefix A is used in this report to refer to measurements carried out in this room.

Pulses of tone were produced by a loudspeaker placed in one corner of the room. An omni-directional microphone was connected through a microphone amplifier to a logarithmic amplifier and thence to an oscilloscope on which the sound decays could be photographed.

Two types of record were produced :

A. With warble tone pulses. The deviation was ± 10% and the warbling frequency 6 c/s about each of seven frequencies from 500 c/s to 8 kc/s. Fifteen microphone positions were used, distributed throughout the room and including three corner positions. The total number of recorded decays was thus 105 for each condition.

B. With pure tone pulses. Starting at each of four frequencies (700 c/s, 1 kc/s, 1·4 kc/s and 2 kc/s), 26 pulses at 2 c/s intervals were recorded using a microphone placed in the centre of the room. There were thus 104 decays for each condition. The choice of 26 pulses covering a band of 50 c/s was intended to provide a sufficiently detailed exploration in the region of each frequency while not extending so far as to involve any changes of mean absorption between the ends of the frequency band.

The average slope of each of the decays was measured from the record and converted to reverberation time. In order to reduce the effect of variations due to individual interpretation of the slope of a decay by a particular observer, each decay was measured by two observers, the two readings being averaged in subsequent computation.

Two quantities were computed :

(1) From the first record, a quantity P representing the variation of slope with microphone position. This was the standard deviation of the 15 individual decays at each frequency expressed as a percentage of their mean slope.

(2) From the second record, a quantity F representing the variation of slope with small arbitrary increments of frequency. This was the standard deviation of the 26 decays in each band, expressed as a percentage of their mean.

2.2. Experiments on the Effect of Distribution of Absorbers

The absorber used for all the experiments was "Tentest Rabbit Warren" which gives efficient absorption from 500 c/s upwards. The experimental conditions are shown in Fig. 1. They were:

Condition A1. 65% of one wall was covered with absorber, the other surfaces being untreated.

Condition A2. The same area of absorber was divided into four sections and mounted on four of the six room surfaces.

Condition A3. One of the four sections was removed, leaving one section on each of three walls mutually at right angles.

Condition A1 was intended to represent a condition of bad distribution of absorption, the distribution being much more uniform in the other conditions. The reverberation time plots are shown in Fig. 2, where it will be seen that although the

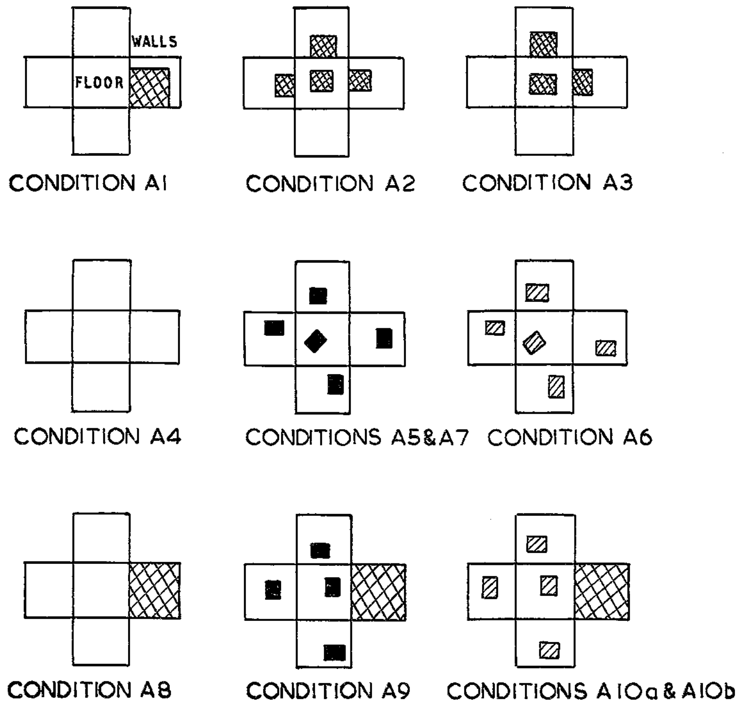

Fig. 1 - Diagrams of room showing disposition of absorbing material and diffusers in various experimental conditions

Absorbing material
Diffusers
Replacement absorbing material

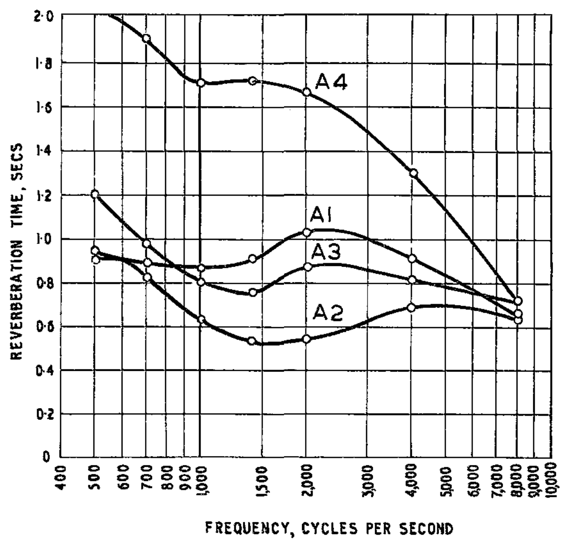

Fig. 2 - Reverberation time of room in experimental conditions A1 to A4

same amount of absorption has been used in the second condition, the reverberation time is appreciably shorter, indicating a greater efficiency of absorption. It was thought possible that the absolute value of the reverberation time might influence the results. It was for this reason that condition A3 was introduced in an attempt to reproduce the reverberation time of condition A1 while substantially maintaining the degree of distribution of condition A2. For comparison another condition, A4, where there was no added absorption, was also investigated. It may be assumed that in this condition the small amount of absorption remaining was perfectly uniformly distributed.

2.3. Results of Experiments with Absorbers

The values of P and F for the four conditions are shown in Table 2 and plotted in Figs. 3 and 4. The values of P for condition A1, where the absorber is

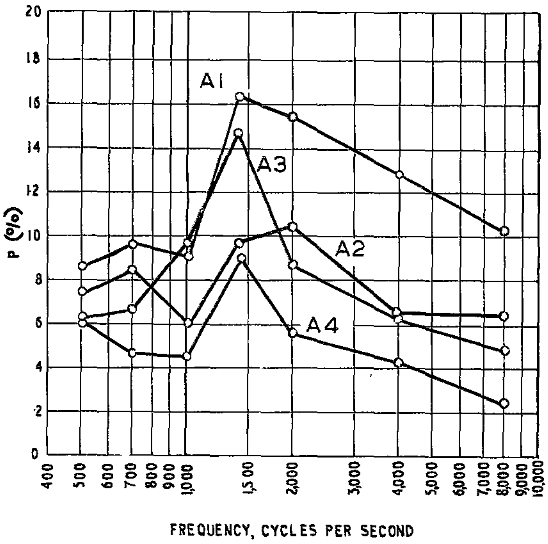

Fig. 3 - Positional variation of reverberation time for experimental conditions A1 to A4

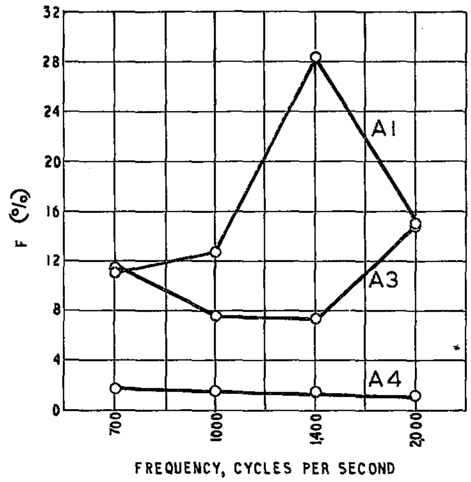

Fig. 4 - Frequency variation of reverberation time (F) for experimental conditions A1, A3 and A4

badly distributed, are generally appreciably greater than those for the other three conditions. The result of distributing the absorber (condition A2) is to reduce the value by about 40% throughout the frequency range. In condition A3, where one of the portions of absorber has been removed, the values are of the same order as those from condition A2 except at 1 kc/s and 1·4 kc/s, where the value returns to that obtained in condition A1. The lowest values are given consistently by condition A4 where the room contained no additional absorption. This will be referred to in the report as the "empty" state.

It thus appears that the quantity P is in general smaller where the absorption is most uniformly distributed, assuming that the absorption in the empty room has the most nearly uniform distribution.

The values of F for condition A1 are very much greater than those for condition A3 at 1·4 kc/s and 1 kc/s, while the empty condition A4 provides very low

values indeed. The quantity F therefore appears to be reduced in value when the absorption is most uniformly distributed.

TABLE 2

Mean Values of P and F with Various Room Conditions

Room Condition	P(%)	F(%)
A1	11·7	16·8
A2	7·9	–
A3	8·2	10·4
A4	5·3	1·4
A5 (mean of two)	5·7	8·4
A6	6·9	9·9
A7	6·3	8·9
Mean of A5 and A7	6·0	–

2.4. Experiment on the Effect of Diffusers

The second experiment was intended to investigate the effect of introducing rectangular diffusers into the otherwise empty room. In condition A5, 12 diffusers were arranged on five of the surfaces of the tiled room. These diffusers were made of stout timber finished with a high gloss paint, and were of three sizes, the largest size being 1 ft 6 in. × 2 ft × 3 ft (46 cm × 61 cm × 92 cm).

The reverberation time in this condition is shown in Fig. 5. It will be seen that throughout the range it is of the order of 50% to 60% of that of the empty room. It is clear, therefore, that the diffusers introduce additional absorption and so for comparison a further condition, A6, was used where the diffusers were replaced by a similar area of absorber.

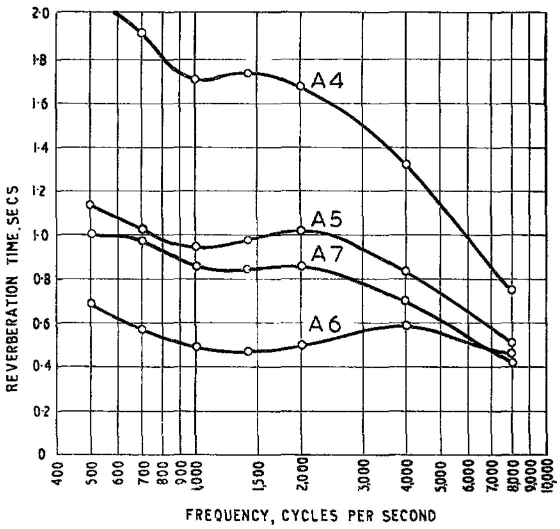

Fig. 5 - Reverberation time of room in experimental conditions A4 to A7

P and F are shown in Figs. 6(a) and 6(b) plotted against frequency, and Table 2 shows the mean values. The values of P for condition A5, shown in Fig. 6(a) are somewhat lower up to 2 kc/s than those for the empty room, condition A4, but rise to a higher value at 4 kc/s. It was thought possible that this might be associated with a corner reflector effect, the right angles between the sides of a diffuser and the wall behaving as corner reflectors for sounds of which the wavelength was small compared to the dimensions of the side. The hypothesis here is that since a corner reflector returns sound along its incident path, it tends to maintain the existing order, rather than creating more disorder, and hence to nullify the effects of the diffuser.

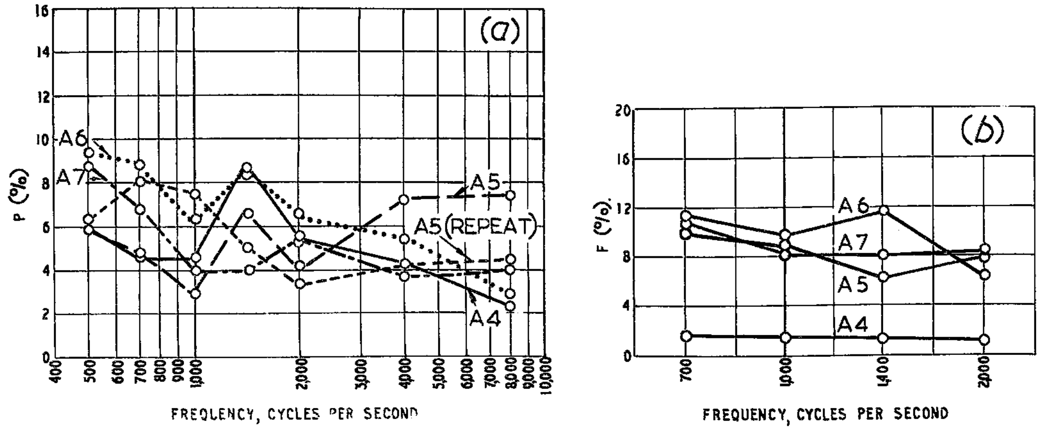

Fig. 6 - (a) Positional variation of reverberation time (P) for experimental conditions A4 to A7
(b) Frequency variation of reverberation time (F) for experimental conditions A4 to A7

In condition A7, therefore, the sides of the diffusers were treated with a thin glasswool felt which had a high absorption coefficient only at high frequencies. The intention was to reduce the corner reflections by absorbing sound of short wavelength.

2.5. Results of Experiments with Diffusers

As can be seen from Fig. 6(a), the values of P for condition A7 are lower than those for condition A5, except below 1 kc/s. Subsequently condition A5 was repeated with a slightly different arrangement of diffusers. The results are shown also in Fig. 6(a). The rise at high frequencies observed in the first measurement is not seen in this case; in fact, the values are largely the same as those for condition A7 though higher below 1 kc/s.

The variations between these three conditions with diffusers present suggest that individual values should be treated with reserve. the general trend only being accepted. The mean for conditions A5 and A7 is shown in the table. Referring to Table 2 and Fig. 6(b) where the mean values of F are shown, it can be seen that the values for conditions A5, A6 and A7 are substantially the same, being similar to those for condition A3. These should be compared with condition A4.

2.6. Further Experiments with Diffusers

In the previous experiments, diffusers as judged in terms of the parameters P and F did not improve conditions in an empty room; here a complication arises in that the diffusers themselves necessarily introduce absorption. In the following experiments the extent to which diffusers could improve an obviously bad condition was investigated.

One wall of the same room was entirely covered with absorbers (condition A8), thus producing a very high degree of spatial asymmetry in the distribution of absorption in the room. In condition A9, 12 diffusers were arranged on the other surfaces of the room, and in condition A10, the diffusers were replaced by patches of absorber. The total absorption contributed by these patches over the frequency range was similar to that of the diffusers; this was verified by a series of special measurements. As it was found very difficult to simulate the diffuser absorption precisely, two variations of this condition were used. In condition A10a, the amount of absorption was too great and in condition A10b, too little. The reverberation time characteristics measured in the room in these conditions are shown in Fig. 7.

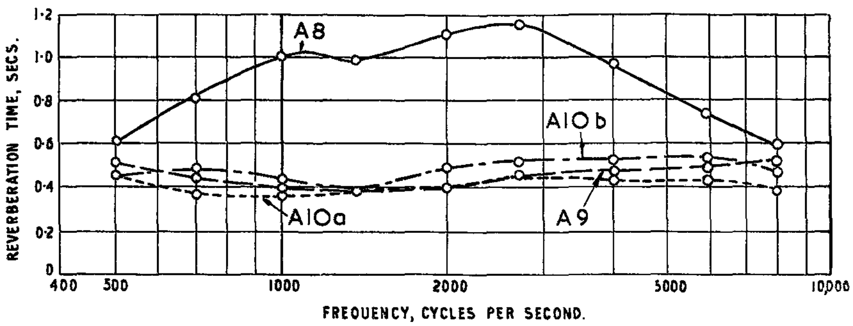

Fig. 7 - Reverberation time of room in experimental conditions A8, A9 and A10

The results in terms of the parameters P and F are shown in Table 3 and in Figs. 8(a) and 8(b). The highest values of P are in general evident in condition A8, as was to be expected. The reduction apparent when diffusers are introduced (condition A9) occurs also when the diffusers are replaced by the larger amount of absorption; in condition A10b, however — that of less absorption — there was a substantial increase in P above 1 kc/s compared with condition A9.

TABLE 3

Effect of Diffusion on the Mean Values of P and F in a Room with Asymmetrical Distribution of Absorption

Room Condition	P(%)	F(%)
A8	13·2	15·6
A9	6·6	9·9
A10 (mean of a and b)	9·0	11·6

The absorption equivalent to that of the diffusers undoubtedly lies between conditions A10a and A10b. Interpolating values of P for these conditions shows that the diffusers have an effect in excess of that to be expected from their absorption alone.

Referring to the values of F observed in the experiments, it is clear that although there is a substantial reduction with the introduction of diffusers, the equivalent absorbers have nearly as great an effect.

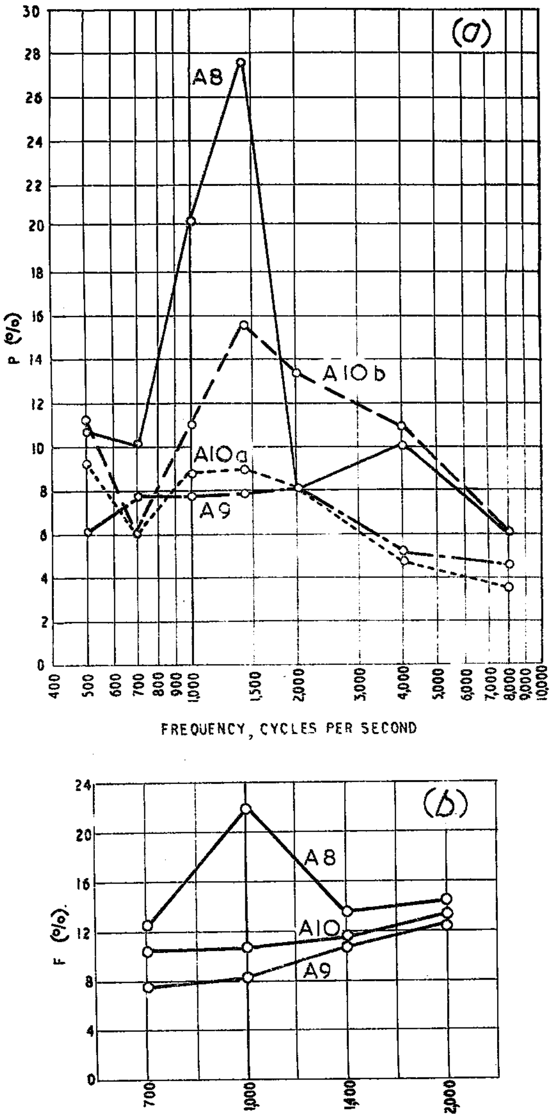

Fig. 8

(a) Positional variation of reverberation time (P) for experimental conditions A8, A9 and A10

(b) Frequency variation of reverberation time (F) for experimental conditions A8, A9 and A10

3. THE STATISTICS OF REVERBERATION TIME MEASUREMENTS IN A ROOM WITH NON-PARALLEL WALLS

3.1. Experimental Conditions

In the foregoing measurements certain general trends are perceptible, though there is considerable variation in the results for any particular condition. These variations could be associated with the exact placing of the absorbers or diffusers, and it was therefore thought desirable to repeat the measurements with different arrangements. Repeat experiments were in fact carried out in another completely tiled room, having a volume of 2,000 ft^3 (57 m^3) and non-parallel walls. Throughout the report conditions in this non-parallel walled room are prefixed B.

The measurement technique was changed in one respect, in that, instead of reading the decay times directly by means of a logarithmic amplifier and oscilloscope, a high-speed logarithmic level recorder was used, giving a paper record. About 100 ft^2 (9 m^2) of absorber was mounted on one wall, leaving about 30% of the wall uncovered. This was intended to reproduce condition A8 used in the smaller room and is referred to as condition B8; similarly the diffusers and absorbers were separately introduced to produce conditions B9 and B10. Later these three conditions were repeated with the absorbers and diffusers re-arranged.

3.2. Results

The results given in Figs. 9, 10 and 11, and in Table 4, show a tendency for the values of P to be lower throughout in room B than in the rectangular room. The difference between the three conditions is less clear. Condition B9, with diffusers, is characterised by the lowest values in the high-frequency region for the first configuration and in the middle frequency region for the second. Although the difference is slight, this condition corresponds to the most consistently low values for the two configurations.

Condition B9 also corresponds with consistently lower values of F than those observed in either of the two other conditions.

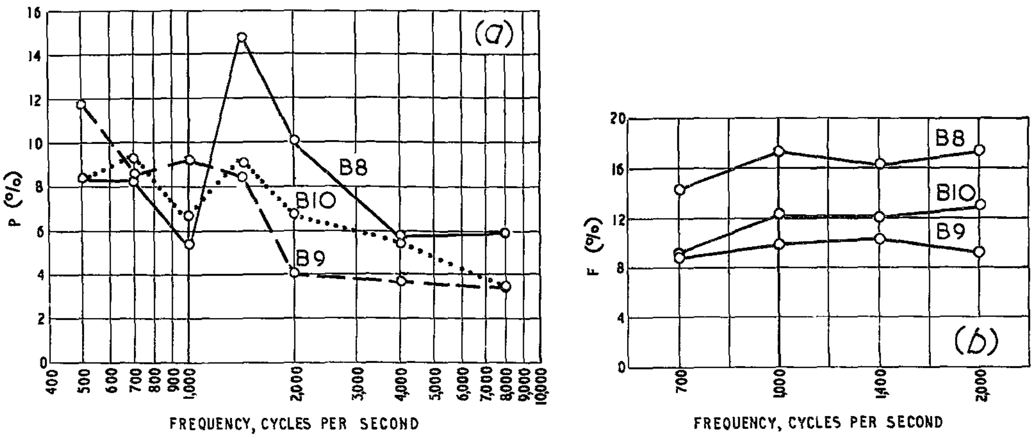

Fig. 9 - (a) Positional variation of reverberation time (P) for conditions B8, B9 and B10
(b) Frequency variation of reverberation time (F) for experimental conditions B8, B9 and B10

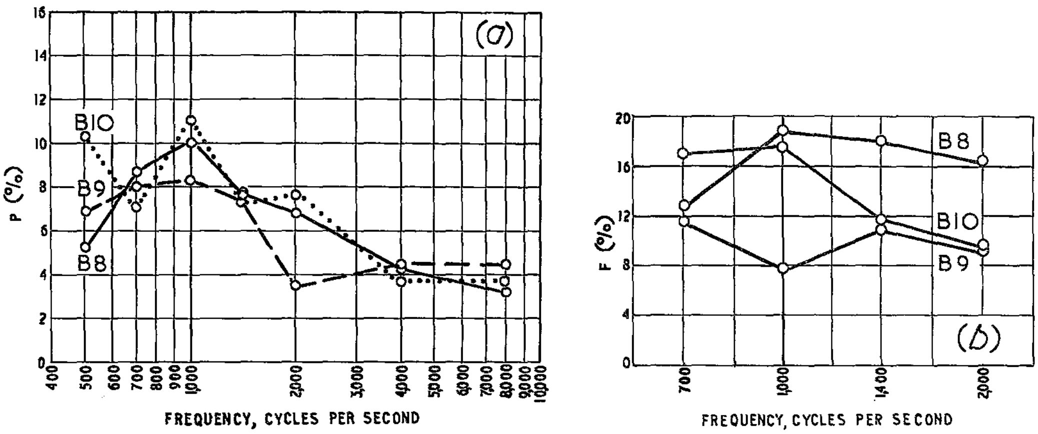

Fig. 10 - (a) Repeat measurements of (P) for conditions B8, B9 and B10 [see Fig. 9(a)]
(b) Repeat measurements of (F) for conditions B8, B9 and B10 [see Fig. 9(b)]

TABLE 4

Mean Values of P and F Measured in a Non-Parallel Walled Room

Room Condition	P(%)	F(%)
B8	8·3	16·4
B9	7·0	9·6
B10	7·1	11·7
B8*	6·7	16·5
B9*	6·3	9·9
B10*	7·5	13·9

*absorbers and diffusers re-arranged

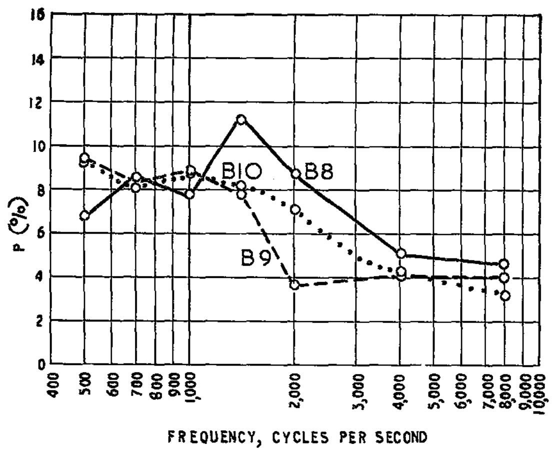

Fig. 11 - Positional variation of reverberation time (P) for conditions B8, B9 and B10 (mean of two determinations)

4. EXPERIMENTS WITH DIRECTIONAL MICROPHONES

4.1. Experiments with a Pressure-Gradient Microphone

An investigation of the directional variations in reverberation time with different conditions in a room was carried out with a type AXBT ribbon microphone. This microphone responds to all components of velocity normal to one plane and has a figure-of-eight polar diagram; considered as a directional microphone, therefore, it has a very broad acceptance angle but has the advantage of a complete null in one plane for all frequencies. The conditions A4, A5 and A6 were investigated, both warble tone and pure tone being used, at mean frequencies over the range 175 c/s to 8 kc/s. With pure tone, two observers made five measurements at intervals of 2 c/s at each frequency, the mean of the ten readings being taken.

In general any differences with orientation were very slight and the investigation in this respect was not pursued further. In Fig. 12 is plotted the result for condition A8 (absorber was mounted on one wall only); this condition, as expected, exhibits the greatest difference between the planes of measurement.

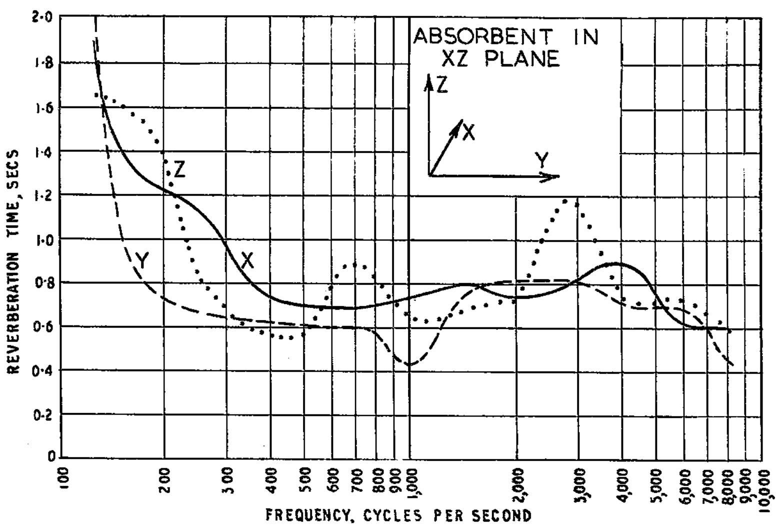

Fig. 12 - Reverberation time measured by pressure gradient microphone in three directions (experimental condition A8)

4.2. Experiments with a Highly Directional Microphone

Subsequently the measurements were repeated using a Labor Type MD82 microphone. This, unlike a ribbon microphone, has an asymmetric polar diagram and a much narrower forward lobe. The microphone consists of a slotted tube, one metre long, containing a graded resistive material, mounted in front of the diaphragm of a pressure microphone. For sound of wavelength less than one metre, partial cancellation takes place along the length of the tube except where the tube lies along the direction of propagation of the wavefront. It presents negligible obstruction in the room but its length is large compared with the wavelength of the standing waves

and represents 30% of the smallest dimension of the room. The signal obtained from it thus does not represent the sound level at a point but is a function of the spatial variation along the length of the microphone.

The results for conditions A8 and A9 are shown in Figs. 13(a) and 13(b). As only one microphone position was used, the mean of two separate determinations is plotted. In general, for condition A8 there was a more pronounced difference between the results obtained for different orientation than with the ribbon microphone. For condition A9, where rectangular diffusers had been added, this difference was appreciably reduced.

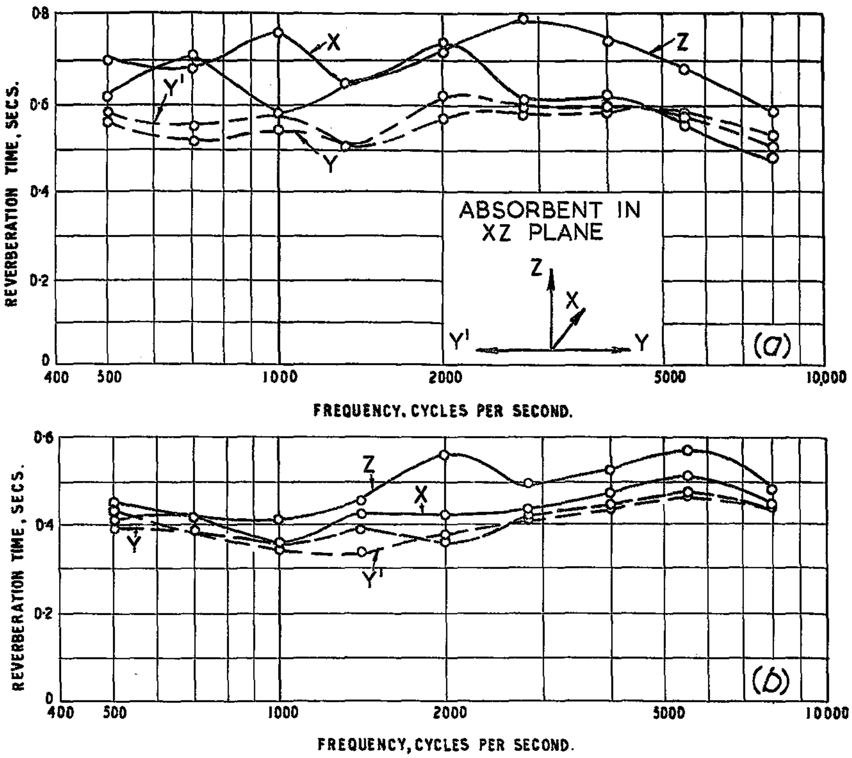

Fig. 13 - (a) Experimental condition A8
(b) Experimental condition A9

Reverberation time measured using highly directional microphone

5. MEASUREMENTS OF THE CURVATURE OF INDIVIDUAL DECAYS

This investigation was confined to a study of the general shape of the decays, no attention being paid to the smaller irregularities. Any change of the exponential index of the decay will appear on the logarithmic scale used for these measurements as a change of slope, which can take one of several forms. The decay may exhibit a single pronounced discontinuity in the slope, several distinct slopes, or even a continuous curve. The shape is usually concave but may on occasions be convex. It was arbitrarily decided to treat all decays as having a double slope, and

an attempt was made to fit straight lines to the top and bottom halves of the decay. The ratio between the two slopes thus obtained represents the simplest way to express the overall linearity of the curve. The records previously used to determine the quantity F were re-examined and the slope of the upper part of each decay was measured by aligning the reference line of the protractor to it while ignoring the lower part. The slope of the lower part was similarly obtained. The division between the two parts of the curve was set at approximately half-way down the decay, which in practice took into account a range of some 25 dB for each part instead of the normal range of 50 dB for the whole decay. This reduction in the level range is the penalty to be paid for obtaining information about the shape of the curve, and the number of measurements must be increased to attain sufficient accuracy in determination of the slopes. Measurements were made by two observers, whose readings were averaged before deriving the ratio between the two slopes. For convenience the slopes were measured in terms of the corresponding reverberation time. In Fig. 14, the values of the reverberation time for the two parts of the decay are plotted for one condition, together with the mean values of the ratio between the slopes. The ratio S, expressed as a percentage, was the fraction:

$$S = \frac{\text{Reverberation time of high slope portion}}{\text{Reverberation time of low slope portion}}$$

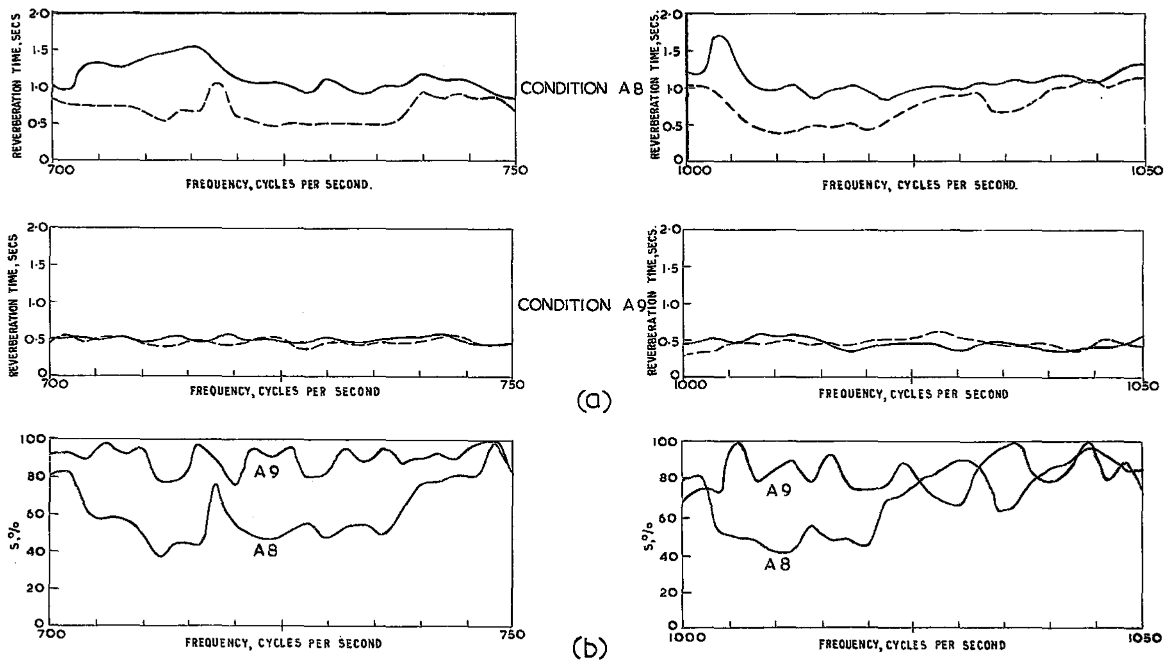

Fig. 14 - Measurement of double slope index (S)

(a) Example of measurements of initial and final slope of decay curves

(b) Values of S obtained from the slope measurements

——— Last part of sound decay

------- First part of sound decay

The reverberation time of the low slope portion is thus defined as the denominator irrespective of whether it occurs in the first or second part of the decay. It follows that the values of S are never greater than 100% (denoting a straight line), and that a given value of S may refer to either a concave or convex decay. An alternative procedure would be to use the reverberation time from, say, the lower part of the decay always as the denominator. In this case a convex slope would be associated with a figure greater than 100%, while a concave slope would still be associated with a figure less than 100% as above. This procedure would have the disadvantage that, in taking a mean of many individual determinations, departures from the straight line as convex slopes would tend to cancel the effect of departure as concave slopes. The resulting mean would not then be the average of the curvature of the individual decays, which is the quantity required.

In practice, as will be seen from Fig. 14, values of the ratio S vary considerably and not always systematically between decays at 2 c/s intervals, so that it was essential to consider the average of a number of individual readings. Means were computed for each of 26 decays, each group covering a range of 50 c/s starting at one of the four frequencies 700 c/s, 1 kc/s, 1·4 kc/s and 2 kc/s.

Table 5 shows the values obtained in eleven room conditions. Study of the table shows that there is no sign of a systematic variation with frequency, so that it appears reasonable to consider the mean of readings taken at all four frequencies as representing a value for any particular condition. Standard errors for these overall means are computed from the 104 readings obtained in each case.

TABLE 5

Effect of Room Condition on the Double Slope Ratio (S%)

Frequency Band Room Condition	700 c/s	1 kc/s	1·4 kc/s	2 kc/s	Mean	Standard Error of Mean
A8	62	69	68	70	67	1·7
A9	91	83	85	86	86	1·0
A10	75	80	71	87	78	1·7
B8	75	74	67	67	71	1·7
B9	75	82	86	84	82	1·4
B10	79	79	76	80	79	1·3
B8*	78	64	69	70	70	1·7
B9*	77	80	80	88	81	1·2
B10*	82	71	68	82	76	1·4
A4	75	79	77	75	77	1·6
A5	75	74	80	81	77	1·5

*absorbers and diffusers re-arranged

Considering first conditions A8, A9 and A10, the lowest value of S corresponding to the highest average curvature was 67%. This occurred in condition A8 in which the only treatment of the room was one wall entirely covered with absorber. When rectangular diffusers were introduced (condition A9), S increased greatly to a value of 86%, indicating that the average decay in this condition was more nearly a straight line. In the check condition (A10) where the diffusers had been replaced by

equivalent absorbers, S had an intermediate value of 78%. The same pattern is evident in conditions B8, B9 and B10 where measurements were made in the room with non-parallel walls, although the range of the means is appreciably less. When the materials were rearranged in the same room and the measurements repeated to provide conditions B8*, B9* and B10*, the values of S agreed very well with those for conditions B8, B9 and B10. The area of absorber in B10* was somewhat greater than that in B10.

The values for conditions A4 and A5 are also listed in the table. These values are not significantly different, indicating that the curvature of the decays is not reduced when diffusers are added to the empty room, where the absorption may be regarded as evenly distributed. The curvature of the decays in these two conditions was greater than in condition A9 where the diffusers were present and the absorption in the room was badly distributed. The apparent anomaly represented by this comparison remains unexplained. It must be noted, however, that conditions A4 and A5 were part of a different set of experiments from those relating to A9 and that the two sets differed widely in their average reverberation times. The reduction of reverberation time between conditions A4 and A9 is sufficient to produce an appreciable alteration in the detailed appearance of the decays, the average number of oscillations for a given level change being reduced. It is thought that such differences in appearance may affect the judgment of an observer in assigning an average slope to part of a decay and lead to systematic deviations where the effect is marked. A direct comparison between A4 and A5 on the one hand and A9 on the other may therefore not be justifiable.

6. REVERBERATION TIME CONTOURS

The magnitudes of the parameter P in the foregoing sections referred to the spread of measured reverberation time in the room but took no account of the manner in which the reverberation time varied throughout the room. The same magnitude of P could be obtained when the readings of reverberation time changed continuously across the room as in the case when there were marked local variations.

In this experiment, reverberation time was measured in about 110 microphone positions at 1 ft (0·30 m) intervals in one plane of a room with 10 ft (3 m) sides. In the first instance, warble-tone pulses were radiated from a loudspeaker and contours of equal reverberation time were plotted on a plan of the room. With this technique the essential information contained in the diagram was masked by unnecessary detail, the form of which varied without apparent change in experimental conditions. The warble-tone technique was therefore discarded.

In the method which proved the most successful, the loudspeaker was supplied with pulses of white noise filtered through 1/3rd octave band-pass filters. In plotting the reverberation-time contours the values of time chosen were running averages from groups of four adjacent microphone positions. It was found convenient to normalize contour levels in terms of percentages of the mean reverberation time because this simplified the comparison of plots having different values of mean reverberation time.

Fig. 15 shows the contour plots for a horizontal plane at half room height for the 1 kc/s filter setting. In the condition represented by Fig. 15(a), the room

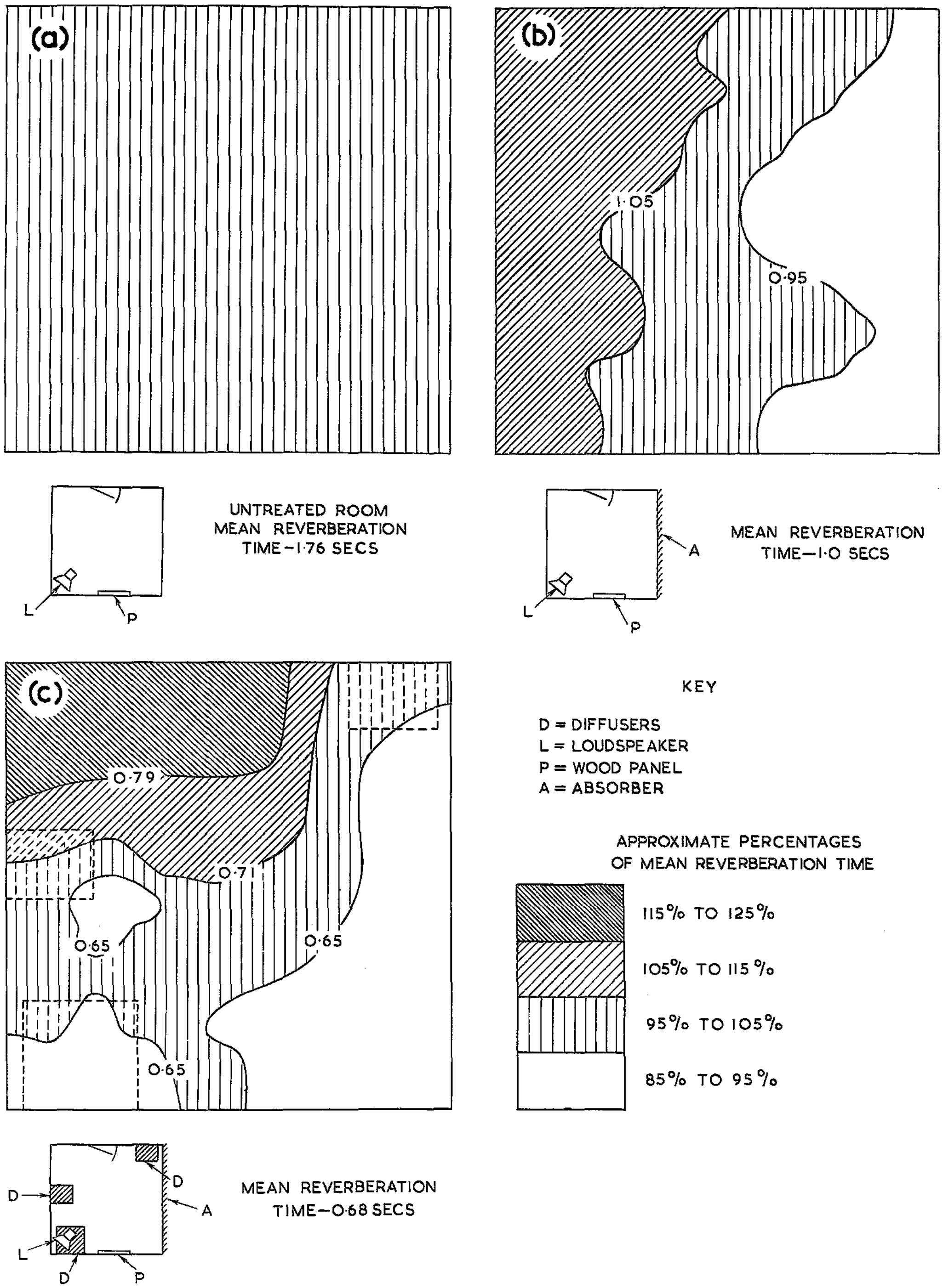

Fig. 15 - Reverberation time contours measured in cubical reverberation room (The experimental conditions appropriate to each plot are indicated in the plan diagrams of the room)

was untreated. No contours are shown, because the closest contours to the mean are at ±5% of the mean and there is no departure greater than 5% in this condition. This illustrates the substantial uniformity of values in the untreated room. In the condition represented by Fig. 15(b), one of the walls was covered with a medium-frequency absorber. The simple pattern indicates the systematic lowering of reverberation time towards the absorbing wall. In Fig. 15(c), which shows the results with three rectangular diffusers fixed to the untreated walls in or near the measurement plane, the pattern has been made more complex by the presence of the diffusers. In each of these diagrams the contour level is 10% of the mean reverberation time.

The work done up to the present is largely exploratory, and these diagrams are included only as examples of the results to be expected. The technique shows promise and may well be developed and applied to the study of broadcasting studios.

7. EFFECT OF DIFFUSION ON THE EFFECTIVE ABSORPTION COEFFICIENT OF AN ABSORBER

Experience suggests that the efficiency of an absorber in a room is related to the degree of diffusion of the sound field in the room. Thus the measured absorption coefficient of a material might be used as an index of the degree of diffusion.

Two experiments were carried out in which this hypothesis was examined.

The first experiment was designed to examine the effects of diffusers on the measured absorption coefficient of a material in the cubical room of 1000 ft^3 (28·3 m^3) volume already described (Room A). Twelve diffusers similar to those described in 2.4 above were mounted on four of the surfaces of the room while 100 ft^2 (9 m^2) of a special standard medium-frequency absorber was mounted in one of the following two ways:

(a) Distributed on five surfaces (between the diffusers). The units were in several sizes, the largest area being 16 ft^2 (1·5 m^2).

(b) Restricted to and completely filling one wall.

The absorption coefficient of the standard sample was determined by measuring reverberation times with and without the sample, (1) without diffusers and (2) with the diffusers in the room. The results are plotted in Fig. 16. Above 500 c/s a considerable difference in the absorption coefficient between arrangements (a) and (b) was observed when no diffusers were present, the absorption coefficient in the 2 kc/s region being reduced to about 25% of its former value when the absorber was concentrated on one wall. In the same condition, however, the absorption coefficient rose to about 75% of the original value when diffusers were present. In arrangement (a) where the absorber was distributed the diffusers had no effect.

It appears, therefore, that diffusers of this sort greatly improve conditions when the distribution of the absorber is extremely bad, but that there is no improvement when the absorber is well distributed and therefore reaches its maximum efficiency without additional diffusers.

The second experiment was intended to find whether, in view of the equivalence of diffusers and absorbing patches found in 2.6 above, distributing the

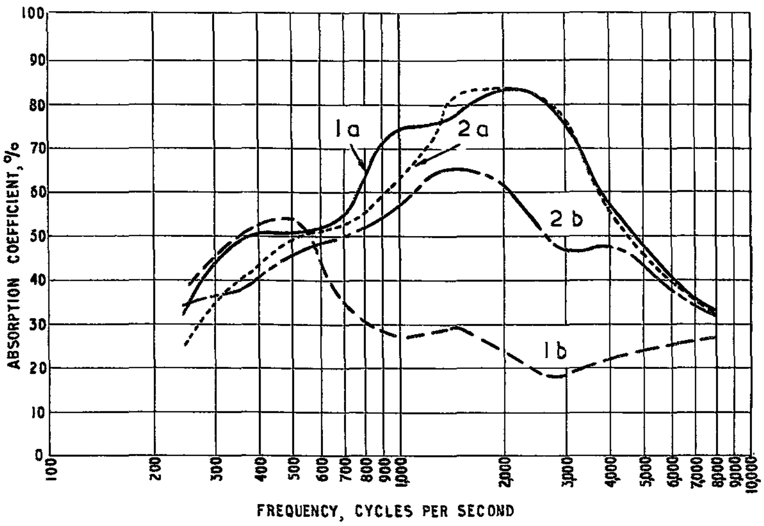

Fig. 16 - Absorption coefficient of fixed area of absorber (a) distributed throughout room (b) concentrated on one wall, and (1) without diffusers (2) with diffusers

absorption evenly was as effective as adding diffusers in increasing the efficiency of a concentrated absorber.

The conditions were similar to those of the first experiment except that Room B [volume 2000 ft³ (57 m³), non-parallel walls] was used. The sample under consideration was restricted to one wall throughout the experiment, additional absorption being provided to produce a diffuse condition when required. Two determinations of the absorption coefficient of the sample were made by measuring reverberation time in four conditions of the room:

(a) Empty.
(b) With the standard sample of area 96 ft² (9 m²) concentrated on one wall.
(c) With the additional absorption distributed around the room.
(d) With additional absorption as in (c) and sample concentrated on one wall as in (b).

Two further conditions were used in order to compare the effect due to distributed absorption with that due to rectangular diffusers in this room. These were:

(e) With 12 rectangular diffusers, no absorber.
(f) With diffusers as in (e) with sample restricted to one wall as above.

The absorption coefficients obtained in these conditions are shown in Fig. 17. Curve 1 was obtained from conditions (a) and (b); curve 2 from conditions (c) and (d); curve 3 from conditions (e) and (f).

It will be seen that in the region above 500 c/s the presence of additional distributed absorption increased the measured absorption coefficient by as much as 30%. This increase is, within experimental error, the same as that obtained when

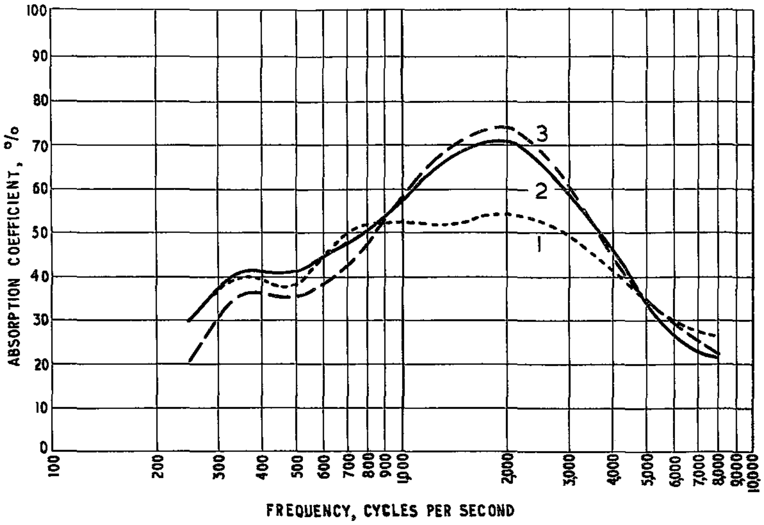

Fig. 17 - Absorption coefficient of absorber concentrated on one wall of room

(1) Room otherwise empty

(2) With additional absorber distributed around room

(3) With 12 rectangular diffusers, no additional absorber

rectangular diffusers were present instead of distributed absorption. This effect is smaller than that obtained for rectangular diffusers in the first experiment, presumably due to the higher degree of diffusion associated with the non-parallel walls and a larger volume in the room used for the second experiment. In fact, the value obtained for the concentrated absorber in the empty room is considerably higher than the equivalent value in the first experiment, taking into account that the absorbers were not the same in the two cases. In both experiments the value obtained with rectangular diffusers was about 75% of that obtained with a distributed absorber (not plotted in Fig. 17).

The results and conclusions from the experiments described in the above section were presented by Mr. T. Somerville to the I.S.O. Conference in Paris in January 1957, but were not published.

8. CONCLUSIONS

8.1. Summary of Conclusions from Individual Experiments

In the foregoing work two interconnected problems have been studied. An attempt has been made to find a measure of the state of diffusion in a room and the physical effects of varying the distribution of absorption and adding artificial diffusers has been investigated. To study these problems together it has been necessary to make certain general assumptions. The first is that the physical quantities studied are those likely to be related to the state of diffusion, and the second is that the room conditions are those that can reasonably be expected to increase or decrease the degree of diffusion.

The investigation became simplified to a series of experiments where room conditions were changed as markedly as possible, and the resulting alterations of each of the physical quantities were examined. Any quantity or parameter which responds to changes in the absorption and the shape of the room may offer a worth-while means of studying conditions in studios and auditoria in general. The experiments show that it is not difficult to detect changes in the sound field as the result of altering the distribution of absorption or of adding artificial diffusers, but, although evidence can be found for changes in several physical quantities, they are not necessarily of practical value for use in experimental investigations in the laboratory or in the field. In some cases a great deal of trouble had to be taken to be sure that a change had indeed taken place, even though the room changes were made as great as possible. The following general conclusions are reached:

1. *Sound Decay Irregularity*

   This parameter was mainly investigated with reference to the effect of diffusers. A great deal of care is required to ensure accuracy and consistency in results; in particular the method is very sensitive to small instrumental variations. It is nevertheless to be noted that the magnitude of the sound decay irregularity was the only quantity which indicated an improvement in the degree of diffusion when diffusers were added to an empty room, although this indication was not pronounced.

2. *Spatial Variation of Reverberation Time (P)*

   This quantity responds quite markedly to changes in the distribution of absorption. This is not surprising, even ignoring general considerations of diffusion, as one might expect to find below-average reverberation times in areas of a room close to surfaces where the absorption coefficient is high. It may well be useful in assessing the behaviour of studios.

3. *Frequency Variation of Reverberation Time (F)*

   There is no obvious reason to expect the variation of reverberation time with small increments of frequency, unlike the spatial variation, to depend on the position of absorbing surfaces. Even so, this quantity gave quite clear indications of changes in the distribution of absorption. It also gave a better indication of the presence of diffusers than the parameter P in a room with inherently poor diffusion. It is considered that this quantity may well be a very useful index for use in field measurements

4. *Variation of Reverberation Time with Orientation of Microphone*

   Although some evidence of change of reverberation time with orientation of the microphone was observed with major changes in the distribution of absorption, little information could be gained under the conditions of these experiments. The evidence of the present work suggests that study of directional effects in small studios is not likely to be fruitful, although important work on similar phenomena in large rooms and concert halls has been reported by Meyer and Thiele.[6]

5. *Sound Decay Curvature (S)*

In the work here described, the curvature was obtained in the simplest possible way by measuring the slopes of the first and second halves of the sound decay curve. It would be possible to extend the principle to derive more subtle measurements of curvature, but in the form here used, where one slope was expressed as a ratio of the other, it is considered to be a very useful index and one which has the advantage of simplicity. It could be derived from existing photographic records (pulsed glide displays) where enough individual decays are visible. In the experiments above it gave clear indications of the presence of bad distribution of absorption and of the effects of artificial diffusers.

6. *Reverberation Time Contours*

Contour diagrams of this kind do not provide a single numerical index of diffusion. The present report gives an account of the first exploratory steps in what may become a useful technique. Investigation is required to determine how to plot the contours so that essential information is retained, and redundant matter discarded. If this can be done the method will be useful for special investigation of studios in which faults in the distribution of absorption are suspected.

8.2. Discussion

In making these judgments of the effectiveness of certain techniques for investigating diffusion, it has been necessary to make assumptions regarding the qualitative effect of distribution of absorption and of artificial diffusers. Having assessed the usefulness of the techniques described in this report it is now possible to draw conclusions regarding the degree to which the state of diffusion is changed by changes in the room, and to compare the effects of distributed absorption and artificial diffusers.

The first experiments, using the indices P and F, showed that when the absorption was restricted to one of the surfaces of a room, the poor degree of diffusion then apparent was markedly improved by a more uniform distribution of the absorbing surfaces over all surfaces in the room.

The presence of diffusers in the otherwise empty room did not appreciably change the degree of diffusion, as indicated by the spatial and frequency variation indices, P and F, or by the double slope index S. The earlier decay-irregularity experiments however had shown a significant improvement with the presence of diffusers.

The effect of diffusers was most marked when they were used for the treatment of a room where the absorption was badly distributed. All three of the indices mentioned above indicated a clear improvement in the degree of diffusion, making due allowance for absorption introduced by the diffusers themselves. The improvement was repeated when variations of the same basic experiment were carried out. It was observed that where measurements were made in a somewhat larger room with non-parallel walls, the difference between treated and untreated conditions was less marked, indicating that the non-parallel walls had been effective in improving the degree of diffusion.

The experiments on the measurement of absorption coefficient, using this quantity as an indicator of diffusion conditions, again showed that where a reasonable uniformity of distribution of absorption over the walls existed, diffusers had no effect on the measured value of absorption coefficient. However, where the absorption was concentrated on one wall, the presence of diffusers effected a marked increase in the measured absorption coefficient. A similar effect on the measured absorption coefficient of this concentrated sample was observed when additional absorption was arranged on the other surfaces of the room. When linked with other experiments, not described here, it was clear that the maximum absorption coefficient measured under these conditions was effectively the maximum absorption coefficient attainable for the material.

Since the above was written, results confirming these conclusions on the relationship between diffusion and the efficiency of absorbers have been published by Meyer and Kuttruff.[7] From results with models, they show that the effective absorption coefficient of a material fixed to the walls of an enclosure may be regarded as a measure of the state of diffusion, and using this criterion they discuss the effect of hemicylindrical diffusers and room shape.

8.3. General Conclusions

Several broad conclusions arise from the work described in this report. The principal conclusion is that practical means are available for the measurement of some at least of the characteristics of good sound diffusion. These are likely to be of value for the investigation of the acoustics of studios and auditoria and in the measurement of absorption coefficients.

The method which appears to be most suitable for adoption as a routine criterion of diffusion in operational studios is that based on the measurement of the average curvature of the individual decay curves. This method is simple and gives a satisfactory indication of changes in diffusion from all causes. It has the additional advantage that existing photographic records of decay curves can in many cases be analysed to obtain the information.

The methods of investigation in this respect taken together show that the degree of diffusion may be improved by the presence of rectangular diffusers and by suitable arrangement of absorbing material, and there is some experimental evidence to confirm the hypothesis that diffusers will effect an improvement even in a room with surfaces of uniform absorption coefficient.

9. REFERENCES

1. Somerville, T. and Ward, F.L., "Investigation of Sound Diffusion in Rooms by means of a Model", Acustica, Vol. 1, No. 1, pp. 40-48, 1951.

2. Research Department Report B-058, Serial No. 1953/29, "Experiments on the Relative Efficiency of Cylindrical and Rectangular Diffusers".

3. Eyring, C.L., "Reverberation Time in Dead Rooms", J.A.S.A. Vol. 1, pp. 217-241, January 1930.

4. Bolt, R.H. and Roop, R.W., "Frequency Response Fluctuations in Rooms", J.A.S.A., Vol. 22, No. 2, p.280, 1950.

5. Somerville, T., "An Empirical Acoustic Criterion", Acustica, Vol. 3, No. 6, p.365, 1953.

6. Meyer, E. and Thiele, R., "Raumakustische Untersuchungen in Zahlreichen Konzertsälen und Rundfunkstudios unter Anwendung Neuerer Messverfahren", Acustica (Beiheft), Vol. 6, pp.425-444, 1956.

7. Meyer, E. and Kuttruff, H., "Nachrichten der Akademie der Wissenschaften in Göttingen", No. 6, January 1958.

10. BIBLIOGRAPHY

Morse, P. and Bolt, R.H., "Sound Waves in Rooms", Reviews of Modern Physics, Vol. 16, p.137, 1944.

Rettinger, M., "Sound Diffusion in Rooms", Audio Engineering, pp. 19, 61, 62, August 1954.

Bolt, R.H., "Normal Frequencies in Rectangular Rooms", J.A.S.A., Vol. 24, p. 80, 1952.

Somerville, T. and Gilford, C.L.S. "Acoustics of Large Orchestral Studios and Concert Halls", Proc. I.E.E., Vol. 104, Part B, No. 14, p.85, 1957.

Bruel, P.V., "Automatic Recording of Frequency Irregularity in Rooms", Acustica, Vol. 4, No. 1, p.21, 1954.

Lamoral, R., "Sur le Coéfficient d'Absorption des Matériaux Acoustiques", L'Onde Electrique, Vol. 33, pp.461-7, July 1953.

Lamoral, R. and Trembasky, R., "Nouvelle Caractéristique Acoustique des Salles et Réalisation d'un Compteur Electronique Polyvalent", L'Onde Electrique, Vol. 36, pp.441-49, May 1956.

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